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Geotechnical investigation and testing — Geotechnical monitoring by field instrumentation —

Part 5:
Stress change measurements by total pressure cells (TPC)

Reconnaissance et essais géotechniques — Surveillance géotechnique par instrumentation in situ —

Partie 5: Mesures de la variation de pression par cellules de pression totale (TPC)

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Contents

Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 182, *Geotechnics*.

A list of all parts in the ISO 18674 series can be found on the ISO website.

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Geotechnical investigation and testing — Geotechnical monitoring by field instrumentation —

Part 5: Stress change measurements by total pressure cells (TPC)

1 Scope

This document specifies the measurement of stress changes by means of total pressure cells (TPC). General rules of performance monitoring of the ground, of structures interacting with the ground, of geotechnical fills and of geotechnical works are presented in ISO 18674-1.

If applied in conjunction with ISO 18674-4, this document allows the determination of effective stress acting in the ground.

This document is applicable to:

— monitoring changes of the state of stress in the ground and in geo-engineered structures (e.g. in earth fill dams or tunnel lining);

— monitoring contact pressures at the interface between two media (e.g. earth pressure on retaining wall; contact pressure at the base of a foundation);

— checking geotechnical designs and adjustment of construction in connection with the Observational Design procedure;

— evaluating stability during or after construction.

Guidelines for the application of TPC in geotechnical engineering are presented in <u>Annex B</u>.

NOTE   This document fulfils the requirements for the performance monitoring of the ground, of structures interacting with the ground and of geotechnical works by the means of total pressure cells as part of the geotechnical investigation and testing according to EN 1997-1[1] and EN 1997-2[2].

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies

ISO 18674-1:2015, *Geotechnical investigation and testing — Geotechnical monitoring by field instrumentation — Part 1: General rules*

ISO 18674-4, *Geotechnical investigation and testing — Geotechnical monitoring by field instrumentation — Part 4: Measurement of pore water pressure: Piezometer*

ISO 22475-1, *Geotechnical investigation and testing — Sampling methods and groundwater measurements — Part 1: Technical principles for execution*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 18674-1 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
total pressure cell
TPC
field instrument for stress change measurements

Note 1 to entry: Typically, a total pressure cell system consists of a pressure compartment, a pressure tubing, a pressure measuring device, a measuring line and a control and readout unit (see Figure 1 and Reference [3]).

Note 2 to entry: The pressure compartment consists of two steel platens, welded together around their peripheries, where the intervening cavity is filled with a liquid. The cavity is connected to the inner chamber of a pressure measuring device via a liquid-filled pressure tubing. Inner and outer chambers of the pressure measuring device are separated by a flexible diaphragm.

Note 3 to entry: Total pressure cells are permanently installed either in fill or soft ground *(embedment pressure cells)* (3.2), in contact planes between any two media *(contact pressure cells)* (3.3) or in boreholes *(borehole pressure cells)* (3.4).

Note 4 to entry: The target of the measurement is the change of the total normal stress $\Delta\sigma_n$ of the medium acting onto the flat side of a pressure compartment (see 1 in Figure 1).

Key
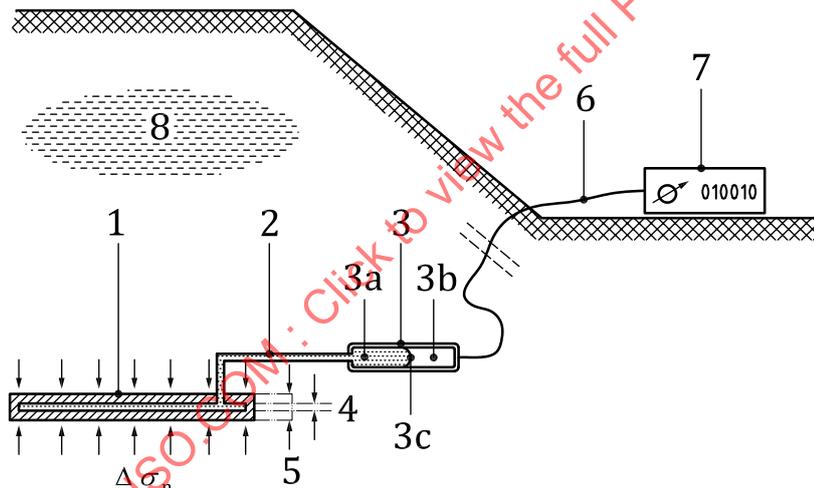
1   pressure compartment

2   pressure tubing

3   pressure measuring device

    3a   inner chamber

    3b   outer chamber

    3c   diaphragm

4   height of the cavity of the pressure compartment

5   height of the pressure compartment

6   measuring line (electric cable or twin hydraulic tubing)

7   control and readout unit

8   medium investigated

Figure 1 — Principal components of a TPC measuring system

3.2
embedment pressure cell
total pressure cell (3.1) which is fully embedded within a medium

EXAMPLE   Push-in cell in soft soil; "tangential cell" in shotcrete tunnel lining (see 4 in Figure 2); embedment cell in fill (see Figure 3).

3.3
contact pressure cell
total pressure cell (3.1) which is placed in a contact plane between two media

EXAMPLE   Cell at the base of a slab foundation; "radial cell" (see 3.9) in shotcrete tunnel lining.

3.4
borehole pressure cell
total pressure cell (3.1) which is installed in a borehole

Note 1 to entry: See 2 in Figure 2.

3.5
aspect ratio
ratio of height to the smallest lateral dimension of the pressure compartment

Note 1 to entry: For rectangular compartments, the smallest lateral dimension is the width, for circular compartments the diameter.

Note 2 to entry: Typical aspect ratios are of the order of 1:20 to 1:40.

3.6
total stress
stress in the ground carried by the solid portion (skeleton) of the ground and the pore water

Note 1 to entry: One only stress component can be monitored by a *total pressure cell* (3.1) (which is the change of the total normal stress $\Delta\sigma_n$).

Note 2 to entry: Changes of 2-D and 3-D stress states can be monitored by a cluster of a sufficient number of independently oriented TPC compartments installed at a measuring location: Three compartments for a 2-D stress state, and six compartments for a 3-D stress state.

Note 3 to entry: By placing a TPC compartment with its sensing side towards the vertical, the vertical normal stress component σ_v can be directly monitored.

3.7
effective stress
stress in the ground carried by the solid portion (skeleton) of the ground

Note 1 to entry: It is $\sigma' = \sigma - u$

where

σ' is the effective stress tensor;

σ is the total stress tensor;

u is the porewater pressure.

The formula above is only applicable to saturated soil.

3.8
contact stress
stress component which acts normal to a contact plane

EXAMPLE   Normal stress acting in the interface between a slab foundation and the ground.

Note 1 to entry: Shear stresses acting within the contact plane cannot be measured by a *TPC* (3.1).

3.9
radial stress
specific *contact stress* (3.8) between the ground and a tunnel lining

Note 1 to entry: Radial *TPCs* (3.1) ("radial cells") are especially designed for monitoring radial stresses.

Note 2 to entry: See 3 in Figure 2.

3.10
tangential stress
hoop stress monitored within shotcrete or concrete tunnel linings

Note 1 to entry: Tangential *TPCs* (3.1) ("tangential cells") are especially designed for monitoring tangential stresses in tunnel linings. An alternative term is "concrete TPC".

Note 2 to entry: See 4 in Figure 2.
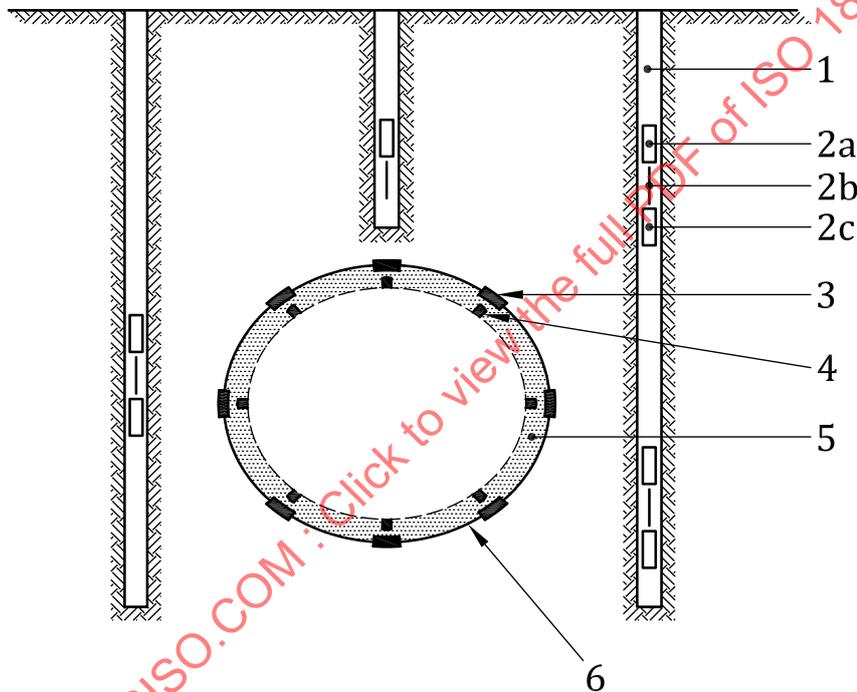
Key

1	borehole (vertically down-dipping; back-filled)
2a, 2b, 2c	array of three differently oriented borehole TPCs for monitoring horizontal ground stresses
3	radial TPCs at the ground/shotcrete lining interface
4	tangential TPCs in the shotcrete lining
5	shotcrete lining
6	tunnel excavation contour

Figure 2 — Example of a TPC layout in near-surface tunnelling
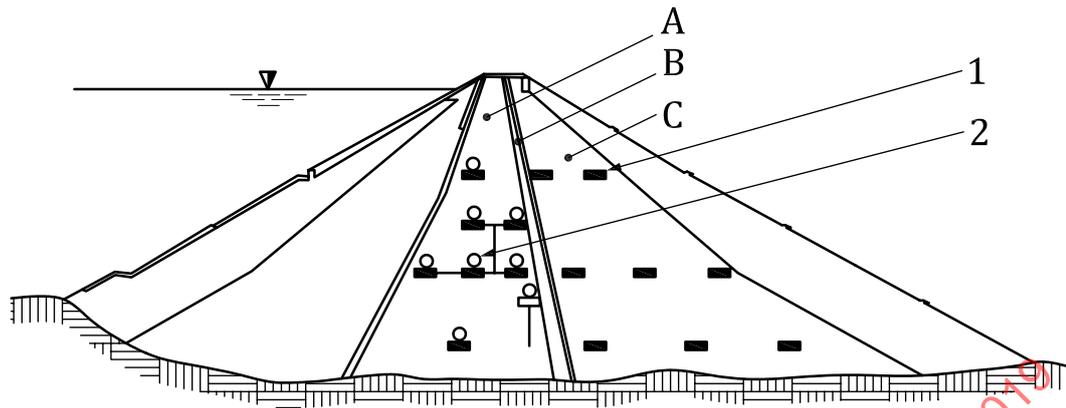
Key

A   clay core

B   filter zone

C   rock fill

1   TPC (single or cluster)

2   piezometer

NOTE   Zones A and C have independent cable routing systems (see 6.1.2.5).

Figure 3 — Example (schematic) of a TPC layout in an earth dam

4   Symbols

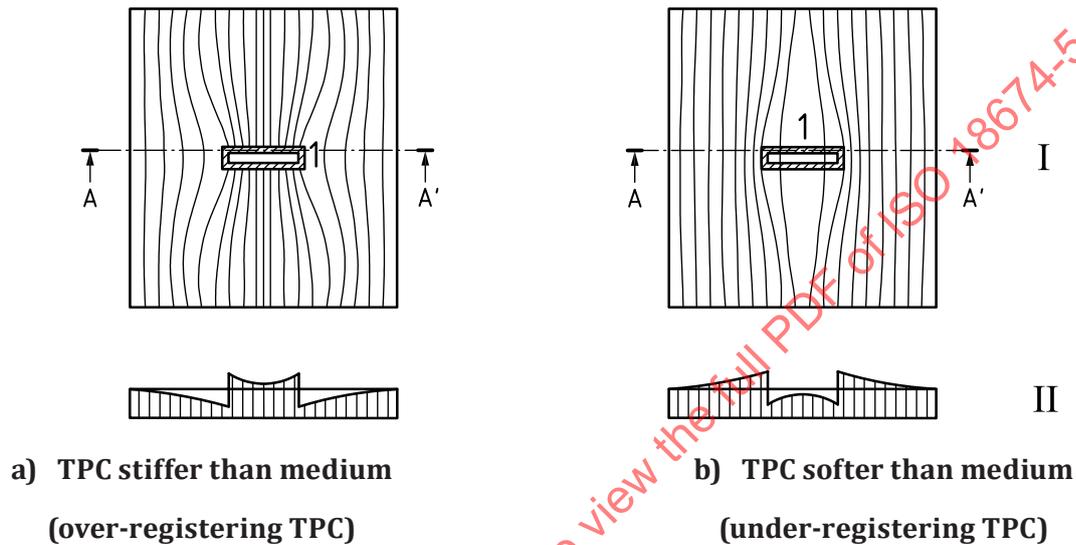| Symbol	Name	Unit
C	edge correction factor	—
E	Young's modulus	MPa
h_1	elevation of measuring station in compensation method	m
h_2	elevation of the TPC in compensation method	m
p_a	pressure in the outer chamber of the measuring device	MPa
p_F	pressure in a follow-up measurement	MPa
p_h	hydrostatic pressure difference between the external measuring station and TPC	MPa
p_i	pressure of the liquid in the compartment and in the inner chamber of the measuring device	MPa
p_L	pressure loss in the compensation delivery line	MPa
$p_{p\text{-}t}$	pre-tensioning pressure	MPa
p_R	pressure in reference measurement	MPa
p_{read}	pressure reading taken at the outside measuring station	MPa
u	pore water pressure	MPa
γ_{fluid}	specific weight of compensation fluid	N/m^3
σ_n; σ_n'	normal stress (total; effective)	MPa
$\Delta\sigma_n$	difference of total normal stress	MPa
σ_v	vertical stress	MPa
σ_H	maximum horizontal stress	MPa
σ_h	minimum horizontal stress	MPa

5   Instruments

5.1   General

5.1.1   It shall be noted that TPC measurements are prone to substantial errors as the presence of the cell in the medium tends to create significant changes in the stress field which is the target of the measurement.

NOTE 1   See Figure 4 (Reference [5]).

NOTE 2   The selection of appropriate instruments, adherence to their range of application and adequate installation procedures are critical to reduce these errors to acceptable levels (see 5.4 and 5.6).

a) TPC stiffer than medium	b) TPC softer than medium
(over-registering TPC)	(under-registering TPC)

Key

I   stress trajectories around a TPC   1   pressure compartment embedded in a medium.

II   normal stress profile A — A'

Figure 4 — Registering effect of embedded TPCs

5.1.2   Deformation and compensation measuring methods should be distinguished from each other (see Table 1).

Table 1 — Monitoring features associated with TPC measuring methods

Measuring method	TPC stiffness	Long-term stability of sensor signal	Atmospheric pressure compensation	Automatic data acquisition	Logging speed
Deformation (see 5.2)	tends to be soft	depends, amongst others, on the type of electrical sensors used	independent barometric pressure monitoring may be needed vented TPC tend to be unreliable	amenable	comparatively quick
Compensation (see 5.3)	tends to be stiff	tends to be long-term stable	vented TPC tend to be reliable	cumbersome; comparatively costly	comparatively slow

5.1.3   Any change of the total normal stress $\Delta\sigma_n$ acting onto the flat side of a pressure compartment (1 in Figure 1) shall be uniquely associated with a change of the pressure of the liquid in the intervening cavity of the compartment.

5.1.4   The stiffness of the pressure compartment in sensing direction should be low in comparison with the stiffness of the pressure tubing and the housing of the pressure measuring device.

5.1.5   The shape and location of the pressure measuring device shall not affect the total normal stress σ_n of the medium acting onto the pressure compartment.

NOTE   A common technical solution is a TPC where the measuring device is located sufficiently far away from the pressure compartment, and where the pressure compartment and measuring device are interconnected by a stiff pressure tubing.

5.1.6   The pressure measuring device (3 in Figure 1) typically is a diaphragm pressure transducer. The cavity of the interconnected components compartment, tubing and measuring device shall be completely filled with, in engineering terms, an incompressible and de-aired liquid. The difference in elevation between compartment and measuring device should be so small that it can be neglected in the evaluation procedure (see A.1.1).

5.1.7   The housing of the pressure measuring device should be sufficiently stiff so that even high ground pressures acting onto the outer side of the device do not affect the mechanical behaviour of the diaphragm, in particular its calibration characteristics.

NOTE   Experience in high embankments has shown that the earth pressure, acting on the housing of a pressure transducer, can cause a substantial shift of the zero-point and a change in the linearity of the transducer.

5.2   Deformation measuring method

5.2.1   The measurement of the deflection of the diaphragm of the pressure measuring device (see 3c in Figure 1) can be used as a method for measuring the pressure of the liquid in the intervening cavities.

NOTE   Commonly, the diaphragm separating the inner chamber and outer chamber coincides with the measuring diaphragm of an electric pressure transducer.

5.2.2   The pressure in the outer chamber of the measuring device (see 3b in Figure 1) shall be either constant or atmospheric.

5.2.3   If TPC measurements are influenced by changes of the atmospheric pressure, thesee should be monitored separately.

NOTE   Attempts to circumvent this issue by integrating a small venting tube into the measuring line (see 6 in Figure 1) are often marred with difficulties, as such tubes tend to become blocked by condensed water. This feature is in contrast to the compensation measuring method (see 5.3 and Table 1).

5.2.4   Deformation measurements carried out directly at the platens of the pressure compartment, e.g. by means of strain gauges or built-in vibrating wire sensors, should be avoided as this measuring procedure will typically result in compartment dimensions with high aspect ratios leading to unfavourable embedment conditions (see 6.1) and ill-defined edge correction factors (see A.1).

5.3   Compensation measuring method

5.3.1   In TPC compensation measuring systems, any changes of the distance between the platens of the pressure compartment caused by $\Delta\sigma_n$ shall be compensated by an externally applied pressure p_a.

NOTE   The common practice is hydraulic application of p_a at comparatively high pressure levels and pneumatic application of p_a at comparatively low pressure levels.

5.3.2   Compensation should be carried out at the diaphragm (3c in Figure 1) of the pressure measuring device. Any deflection of the diaphragm, as described in 5.2.1, shall be compensated by a pressure p_a acting in the outer chamber of the device.

5.3.3   The compensation point shall be clearly defined and well identifiable when making the measurement. Pressure valve or electric diaphragm switch techniques may be employed.

5.4   Stiffness of the pressure compartment

In sensing direction, the stiffness of the pressure compartment should conform to the stiffness of the medium.

NOTE 1   Stress concentration effects influence the measuring results yielding either systematically too low or too high values (see Figure 4).

NOTE 2   Amongst the factors which influence the stiffness of the TPC system are the following:

— measuring principle (deformation, see 5.2, versus compensation, see 5.3; see also Table 1);

— aspect ratio;

— height of liquid-filled cavity (4 in Figure 1);

— volume and compressibility of the liquid in the closed inner system;

— deformability of the housing of the closed inner system (see 5.1.7).

NOTE 3   Further difficulties arise when the stiffness of the medium is changing in course of the monitoring project, e.g. consolidation of fill or curing of shotcrete. For further influencing factors, see Reference [4].

5.5   Shape of the pressure compartment

5.5.1   The shape of the pressure compartment can be rectangular, square, oval or circular. If not affected by other constraints (e.g. construction; shape and dimension of medium or contact), circular shapes should be preferred.

NOTE 1   Common compartment dimensions are diameters, respectively edge lengths, of the order of 100 mm to 400 mm.

NOTE 2   Common for soils and fine-grained fill are circular compartments with a diameter of about 120 mm to 300 mm; for ground/concrete contacts rectangular compartments of 200 mm × 300 mm; for ground/tunnel lining contacts radial compartments of 150 mm × 250 mm and for tunnel lining embedment tangential compartments of 100 mm × 200 mm.

5.5.2   The aspect ratio should not be higher than 1:15 for soil and fill and not be higher than 1:25 for rock and concrete. Compartments with small aspect ratios shall be preferred, provided that the compartment platens will not touch each other across the liquid-filled cavity.

NOTE   Commonly, TPC compartments are about 4 mm to 12 mm thick.

5.5.3   The selection of the compartments should be made in consideration of the influence which edges and corners of the pressure compartments can have onto the stress distribution around the compartment (Figure 5) and thus onto the measurement. Figure 6 shows two technical solutions which are reducing the edge effect. These solutions should be considered in the TPC selection.

NOTE   Edges and corners of pressure compartments are commonly stiffer than the sensing area of the compartments and, thus, are attracting over-proportionally high stresses. This effect is particularly relevant for high aspect ratios.
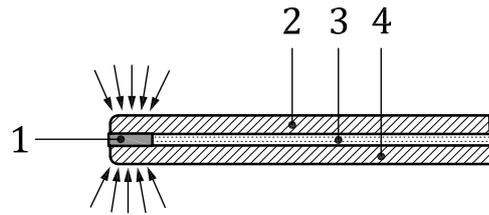
Key

1 weld seam
2 top platen
3 liquid-filled cavity
4 bottom platen

Figure 5 — Edge effect of pressure compartments: stress concentration at comparatively stiff edge (schematic)

a) Flexible edge solution

b) Edge groove solution

Key

1 weld seam
2 stiff bearing plate
3 liquid-filled cavity
4a flexible cover plate
4b bottom plate
5 groove

Figure 6 — Examples of technical solutions for reducing edge effects

5.5.4   In aggressive media, e.g. in sulphatic rock or groundwater, the TPC material should be corrosion-resistant.

5.5.5   In the case that, after the completion of the monitoring project, TPCs are left in the ground, attention shall be paid to the compatibility of the material, in particular of the cell liquid, to the environment.

EXAMPLE   Use of bio-degradable hydraulic oil.

5.6 Accuracy

5.6.1   It shall be realised that the degree of conformity between the embedded TPC and the surrounding medium is critical for the accuracy of the TPC system.

NOTE 1   The degree of conformity is difficult to specify (see 5.4, NOTE 2) and often subject to changes in course of the measuring project (see 5.4, NOTE 3).

NOTE 2   A calibration of the combined TPC components (compartment, tubing and measuring device; see Figure 1) in a pressure enclave is not indicative of the accuracy of the TPC system as it yields (near-)perfect results for almost any shape of the compartment and any pressure measuring device.

NOTE 3   Manufacturers commonly specify the accuracy of the TPC pressure transducer (see 3 in Figure 1), for instance, accuracy ±0,1 % full scale. This accuracy is not that of the TPC.

5.6.2   The accuracy of a TPC system may best be estimated by plausibility checks of the field measuring results and by independent information.

NOTE   See 6.1.2.7.

5.6.3   Laboratory tests for determining the accuracy of the TPC system shall only be carried out if the intended installation procedure is reproduced in the set-up of the test.

NOTE   Realistic calibration tests of TPC systems in the laboratory are expensive and only justified in exceptional circumstances.

6   Installation and measuring procedure

6.1   Installation

6.1.1   Installation in the ground

6.1.1.1   In soft soil, TPCs should be pushed-in by appropriate equipment, e.g. by a CPT rig in accordance to ISO 22476-1. Measurements shall commence after dissipation of any excess porewater pressure which may have developed in connection with the TPC installation.

NOTE   Specially designed TPCs, often with a built-in piezometer, are commercially available from various sources.

6.1.1.2   In stiff soil and rock, TPCs should be installed in boreholes. The boreholes shall be drilled in accordance with ISO 22475-1. The TPC, or the array of several TPCs (see Figure 2), shall be placed and fixed in the borehole whilst controlling the depth and orientation of the compartment sensing direction.

6.1.1.3   At the measuring location, the borehole shall be backfilled with a material which is adjusted to the stiffness of the ground.

EXAMPLE 1   For soft rocks and stiff soils (E < 5 GPa), bentonite and other low-strength cement suspension in combination with clayey components.

EXAMPLE 2   For moderately stiff rock (5 GPa ≤ E < 20 GPa), cement-based mortar or suspension.

EXAMPLE 3   For stiff rocks (20 GPa ≤ E < 30 GPa), dental mortar in combination with subsequent pre-stressing of at least 0,5 MPa.

6.1.1.4   After cure of the backfill material, it shall be secured that a complete and intimate contact is established between the TPC compartment and the borehole wall and that the TPC set-up is pre-tensioned (see Table 2). This may be achieved by expansion of the compartment, e.g. by squeezing of a pinching tube (see 6.1.3.3 and Figure 7), or by contact grouting. In the latter case, grouting tubes should

be laid to each compartment. The effective grout pressure at the measuring location should be at least of the magnitude of the pre-tensioning pressure $p_{p\text{-}t}$ specified in Table 2, maximally twice that magnitude.

Table 2 — Pre-tensioning pressure $p_{p\text{-}t}$ of TPC installations in stiff soils and rocks

Young's Modulus of medium MPa	pre-tensioning pressure $p_{p\text{-}t}$ MPa
very low (<100 MPa)	0,02
low (100 to 5 000 MPa)	0,05
medium (5 000 to 20 000 MPa)	0,10
high (20 000 to 30 000 MPa)	0,50
very high (>30 000 MPa)	not applicable

6.1.1.5   Measurements can commence after completion of pre-tensioning and stabilisation of the TPC measuring signal.

6.1.2   Installation in fill

6.1.2.1   TPC installation should commence when the fill has reached a height of at least 800 mm above the instrument level. A wide bottomed excavation with smaller than 1:3 sloped sides in all directions shall be formed. The size of the excavation should depend on the number of TPCs to be installed.

EXAMPLE   The installation of a cluster of three TPCs commonly requires an excavation base of the order of 4 m × 4 m (see a measuring example in C.2).

6.1.2.2   The TPC should be placed and fixed in position right at the excavation base. There should not be separate pockets in the base for accommodating individual TPCs. Prior to the TPC placement, the base of the excavation should have been (re-)compacted. A thin, continuous layer of a low-strength sand-cement mixture may be applied for stabilisation of the installation base.

6.1.2.3   In clusters, the minimum spacing of adjacent TPCs shall be three times of the TPC dimension, typically about 1,5 m.

6.1.2.4   Pressure cells and measuring lines shall be robust to survive the harsh environment typical for earth dam construction. There shall be a provision for slack in the measuring lines to accommodate large strains.

6.1.2.5   Measuring lines should not be routed through zones of potentially excessive shear such as the core-filter-shell transition zone (see B in Figure 3). If such zones cannot be avoided, the lines shall be designed to withstand the expected shear movements and to avoid water flow along the lines.

NOTE   An attempt to meet that requirement is the use of an external corrugated sleeving where the ring gap between sleeve and measuring line is filled with an erodible-resisting, deformable material of low permeability.

6.1.2.6   After placement of the TPC and routing of the measuring lines, the excavation should be backfilled in lifts of about 100 mm to 200 mm with embankment material at unchanged water content, having removed aggregates larger than 25 mm. Each lift should be individually compacted by hand-operated equipment, before the general compaction procedure takes over some 800 mm above the installation level.

6.1.2.7   After installation, TPC performance checks should be carried out as early as possible.

NOTE   Consideration of the overburden pressure, which is steadily increasing with the placement of the fill, is useful in that regard. In the lower portion of an embankment dam, the stress field during construction is essentially 2-dimensional if the valley is wide and not predominately V-shaped. In this case, it is reasonable to compare the calculated vertical stresses σ_v, as deduced from the density and thickness of the fill, with the measured values. This procedure is commonly used to check the performance of TPCs installed in high embankments.

6.1.3   Installation in concrete/shotcrete

6.1.3.1   The TPC shall be securely fixed, e.g. by soft iron wire to reinforcement bars or nearby steel sets, to ensure that the position and alignment of the TPC compartments are maintained during pouring of concrete (applying of shotcrete). Care should be exercised to avoid air entrapments (spray shadows) when placing the concrete (applying the shotcrete).

NOTE   In shotcrete tunnel linings, fixation of the TPC to steel mesh is often not sufficient, as shotcreting-induced mesh vibrations can deter from a good-quality TPC embedment.

6.1.3.2   For measurements in concrete, containing aggregates larger than 25 mm, it is advisable to surround the TPC in a special concrete mix from which the coarser aggregate particles have been removed.

6.1.3.3   The shrink gap between the compartment sensing surface and concrete (shotcrete), which regularly develops towards the end of the curing process, shall be closed prior to carrying out the measurements. For this purpose concrete embedment TPCs shall be equipped with a pre-stressing device (5 in Figure 7) which should allow at least three pre-stressing actions.

EXAMPLE 1   Liquid-filled pinching tube which is connected with the intervening cavity of the TPC compartment and which is long enough to protrude from the concrete (shotcrete) (see Figure 7).

EXAMPLE 2   Injection line routed directly into the gap for pre-pressure grouting

NOTE   The longer the pinching tube the less stiff is the pressure cell.

6.1.3.4   The tubing of the pre-stressing device should be routed in such way that it is protected from construction work and shielded from temperature changes.

NOTE   Changes of the ambient temperature at the pinching tube influence the cell pressure.

6.1.3.5   Measurements can commence after completion of pre-stressing and stabilisation of the TPC measuring signal.

Key
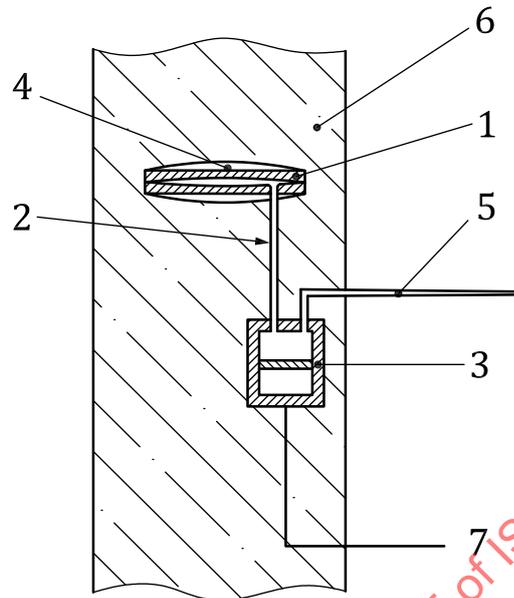
1   pressure compartment at a stage after dissipation of cure temperature
2   pressure line
3   pressure measuring device
4   shrink gap
5   pre-stressing device (pinching tube)
6   concrete (shotcrete)
7   measuring line

Figure 7 — Possible layout of a concrete embedment TPC with pinching tube

6.1.4   Installation in contact planes

6.1.4.1   Contact TPCs shall be installed and fixed flush with the interface of the seating medium.

EXAMPLE 1   Earth pressure on concrete abutment (see C.3).

EXAMPLE 2   Rock pressure onto tunnel lining (see C.4 a).

6.1.4.2   In case of an irregularly shaped seating plane, e.g. rock surface excavated by drilling and blasting, the compartment of the TPC shall be placed on a bed which levels out the irregularities. The bedding material should be of similar stiffness than the seating medium. The bed thickness should be as small as practically possible.

6.1.4.3   The cover medium shall be placed uniformly onto the seating medium and the TPC compartment. It shall be secured that the compartment is fully covered by the new material.

EXAMPLE   Typical cover materials are: backfill acting against concrete abutment; soil acting against sheet pile wall; shotcrete lining acting against ground pressure in tunnels ("radial TPC").

6.2   Carrying out the measurement

6.2.1   Instrumentation check and calibration

6.2.1.1   The TPC assembly should be function-checked prior to the installation and before commencing with the measurements.

6.2.1.2   Peripheral components such as pressure gauges and readout devices shall be calibrated before and after the TPC monitoring project and, if applicable, every two years.

6.2.2   Measurement

6.2.2.1   The TPC fluid pressure p_i shall be measured either by the deformation or the compensation measuring method, as appropriate (see Table 1).

6.2.2.2   Whilst taking the measurements, or immediately after the measurements, the measured data should be checked on its plausibility. In the case of unexpected or contradicting data, the measurements shall be repeated.

7   Data processing and evaluation

7.1   Processing and evaluation of the TPC measuring data shall be carried out according to Annex A.

7.2   Preliminary processing and evaluation of the data should be carried out immediately after taking the measurements.

7.3   Data processing shall contain the determination of the stress change $\Delta\sigma_n$ after Formula (A.3), the tabulation of the measured values and the presentation of the values in diagrams where, for each TPC, the stress changes should be graphed over the time.

EXAMPLES   See Annex C.

7.4   If applicable, the particulars of the construction process shall also be documented and marked in the tables and diagrams.

EXAMPLE   Indication of the time when distinct tunnel excavation stages (top heading; benching; closure of the invert) are passing the measuring section.

8   Reporting

8.1   Installation report

The installation report shall be in accordance with ISO 18674-1:2015, 9.1.

8.2   Monitoring report

The monitoring report shall be in accordance with ISO 18674-1:2015, 9.2.

Annex A
(normative)

Evaluation procedure

A.1 Normal stress σ_n acting onto the pressure compartment

A.1.1 The total normal stress σ_n of the medium acting onto the pressure compartment of the TPC shall be calculated as follows:

$$\sigma_n = p_i \cdot C \tag{A.1}$$

where

p_i is the liquid pressure in the TPC compartment;

C is the cell edge correction factor with $C \geq 1$.

NOTE   Commonly, commercially available TPCs have insignificant elevation differences between pressure compartment (1 in Figure 1) and pressure measuring device (3 in Figure 1). Any such differences are not considered in this evaluation procedure.

A.1.2 The effective normal stress component σ_n' of the medium acting onto the TPC compartment shall be calculated as:

$$\sigma_n' = \sigma_n - u \tag{A.2}$$

where

u is the pore water pressure as measured according to ISO 18674-4.

A.1.3 Commonly, the edge correction factor C is only significant for aspect ratios higher than 1:20 (e.g. 1:10). In that case, the factor C should be specified in the Instrument Data Sheet. If, for the type of medium of concern, the factor is not readily available, dedicated control tests may be carried out in a compression testing machine. For this purpose, a TPC should be embedded in a medium sample of the dimension of at least three times the dimension of the TPC.

A.2 Stress change

The stress change $\Delta\sigma_n$ which has occurred after the installation of the TPC is as follows:

$$\Delta\sigma_n = (p_F - p_R) \cdot C \tag{A.3}$$

where

p_F is the pressure in a follow-up measurement;

p_R is the pressure as measured after completion of TPC installation and taken as reference measurement.

A.3   Evaluation of compensation measurements

A.3.1   When employing the compensation measuring method (see 5.3) it is:

$$p_i = p_a \tag{A.4}$$

where

p_a is the compensation pressure applied from the outside.

A.3.2   Specifically, it is:

$$p_a = p_{read} + p_h + p_L \tag{A.5}$$

where

p_{read} is the pressure reading taken at the outside measuring station;

p_h is the static head correction for the pressure due to difference in elevation between the TPC and the measuring station;

p_L is the pressure loss due to friction in the compensation delivery line.

A.3.3   The static head (elevation) correction p_h can be calculated as follows:

$$p_h = \gamma_{fluid}(h_1 - h_2) \tag{A.6}$$

where

γ_{fluid} is the specific weight of the fluid in the compensation delivery line (for gas: $\gamma = 0$);

$h_1 - h_2$ is the difference in elevation between measuring station and TPC (positive if TPC is below station).

A.3.4   The tube friction correction factor p_L can be relevant in a pressure valve compensation measuring system (see 5.3). That factor should be measured during installation, before connecting the TPC to the tubing. The factor p_L is the pressure required to maintain a steady flow through the tubing at a flow rate similar to that obtained during measurement. Under normal conditions, with unobstructed and correctly selected tubing, p_L should be small in comparison to the compensation pressure p_a.

Annex B
(informative)

Geo-engineering applications

Table B.1 provides an overview of the various types of total pressure cells in some common geo-engineering applications. The classification, as shown in Table B.1, may assist in the instrument selection. In the case that a geo-engineering application is not included in Table B.1, the closest application can be considered for the selection.

Table B.1 — Guide for the selection of TPC types in geo-engineering applications

Application	Suitability of TPC instrumentation			
	TPC type and typical compartment size dimension [mm]			
	Embedment	Contact	Push-in	Borehole
Earth dams and embankments	+ 400 × 400	-	+/- Ø 200	-
Shallow foundation on soil or fill	-	+ 400 × 400	-	-
Cast-in-place pile foundation	+/- Ø 600	-	-	-
in soft soil	-	-	+ Ø 200	-
in stiff soil and soft rock	-	-	-	+ 150 × 200
in hard rock	-	-	-	+/- 100 × 200
Tunnel lining: Radial stress	-	+ 150 × 250	-	—
Tunnel lining: Tangential stress	+/- 100 × 200	-	-	—
Underground repositories	+ (for fill) 400 × 400	-	-	+/- (for rock) 100 × 200
Swelling of the ground		+ 150 × 250		+/- 100 × 200

Annex C
(informative)

Measuring examples

C.1 General

Examples of the various types of total pressure cells and typical applications are presented as follows:

a) Earth pressures in a rock fill dam (see C.2);

b) Earth pressures acting onto the sidewall of a lock chamber (see C.3);

c) Radial and tangential stresses in a concrete tunnel lining (see C.4).

Each example contains information that is typically included in a report in accordance with ISO 18674-1:2015, Clause 9.

C.2 Earth pressures in a rockfill dam

|		
a)	Owner of the project	Iran Water and Power Resources Development Co., Tehran, Iran.
b)	Name and location of the project	Masjed-e-Soleiman (MES) Hydroelectric Power Project, Iran.
c)	Name of the company carrying out the monitoring project	JV Nippon Koei — Moshanir — Lahmeyer International.
d)	Monitoring project	177 m high zoned rock-fill dam with a central symmetric clay core.
e)	Instrumentation	48 clusters of earth pressure cells, distributed over the core, filter zone and downstream rock fill. Each cluster consists of three TPCs (inclination –45°, 0° and +45° towards the dam axis), supplemented by a single vibrating wire piezometer.
f)	Instrumentation details	Total pressure cells, diameter 270 mm. Deformation measuring principle (vibrating wire pressure transducer; electric cable). Vibrating wire piezometer, measuring range 2 000 kPa.
g)	Installation details	Installation of each TPC cluster at the base of an approximately 4 m × 4 m wide and 0,8 m deep trench, sloped at about 1:3. No extra pockets for individual TPCs.
h)	Commissioning of the monitoring system	Step-by-step commissioning in line with progressing embankment construction.
i)	Measurements	Continuous data logging.
j)	Measuring uncertainty	Unspecified. Predominately subject to quality of installation.

k) Principal results of the monitoring project

Built-up of earth pressures in line with the embankment construction (increasing height h of the dam). Monitoring of the built-up of total stresses by the three TPCs placed at a measuring point and determination of the 2-D stress state in the dam axis. Near-steady-state conditions at completion of embankment construction and during impounding (see Figure C.1). Simultaneous monitoring of the porewater pressure built-up in the clay core (not shown in Figure C.1). Determination of the stress paths in p-q — diagrams (Figure C.2 a for total stresses and Figure C.2 b for effective stresses).

NOTE $p = (\sigma_1 + \sigma_2) / 2$ $p' = [(\sigma_1 + \sigma_2) / 2] - u$
$q = q' = (\sigma_1 - \sigma_2) / 2$

where:

σ_1 and σ_2 are maximum and minimum principal stresses derived from TPC measurements;

u is the porewater pressure as measured by piezometer.

l) Assessment and evaluation of the measuring results

High degree of homogeneity of built-up of total stresses in the clay core: Almost identical response at the down-stream side (3a in Figure C.1) and in the centre of the core. Identical results for the porewater pressure measurements (not shown in Figure C.1). State of near-zero effective stresses in the clay core (Figure C.2, bottom).

m) Reference

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Key
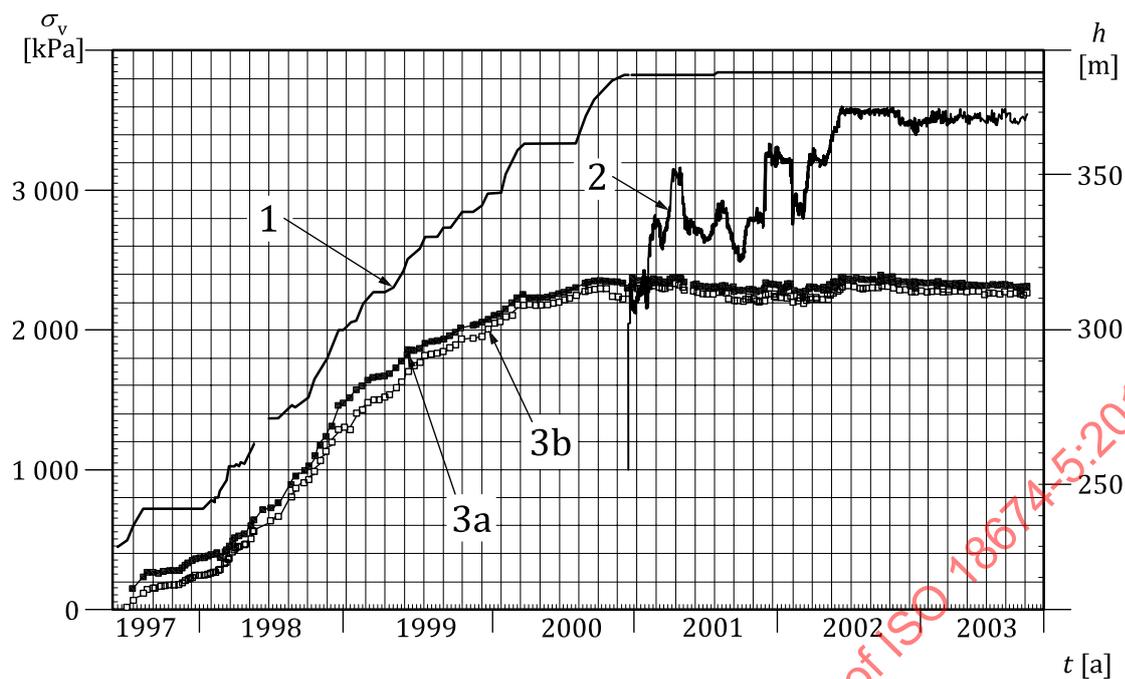
σ_v	measured total vertical stress [kPa]	1	actual height of dam in course of construction [m]
h	elevation above sea level [m]	2	water level of reservoir [m]
t	time [a]	3a	total vertical stress, core down-stream side, EL 230
		3b	total vertical stress, core centre, EL 230

Figure C.1 — Example of the built-up of total vertical stresses in line with the construction of the dam and initial impounding
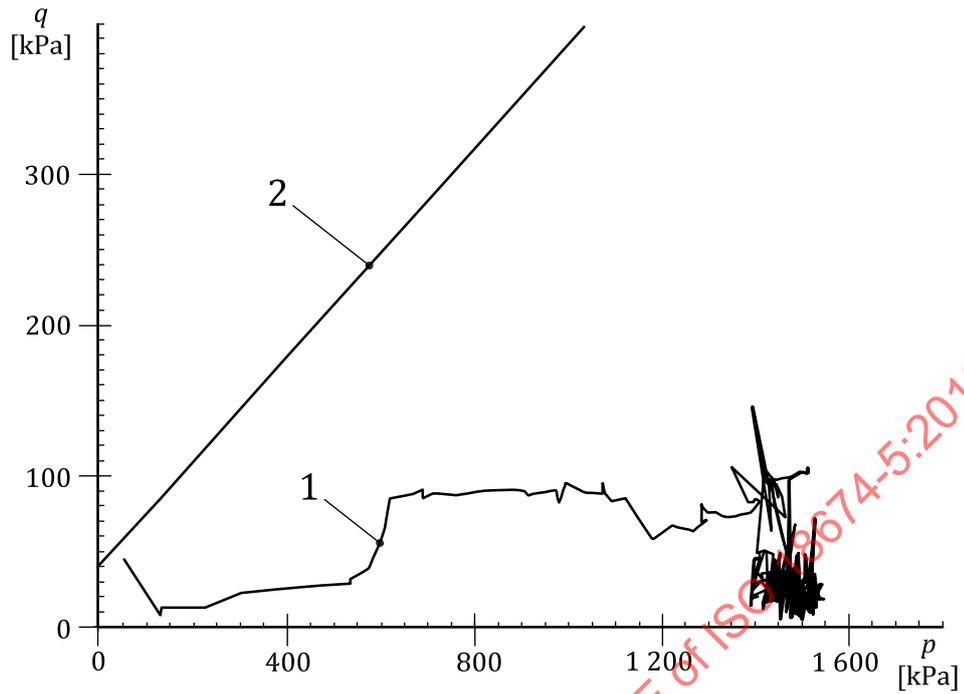
a) total stress plot *p-q*
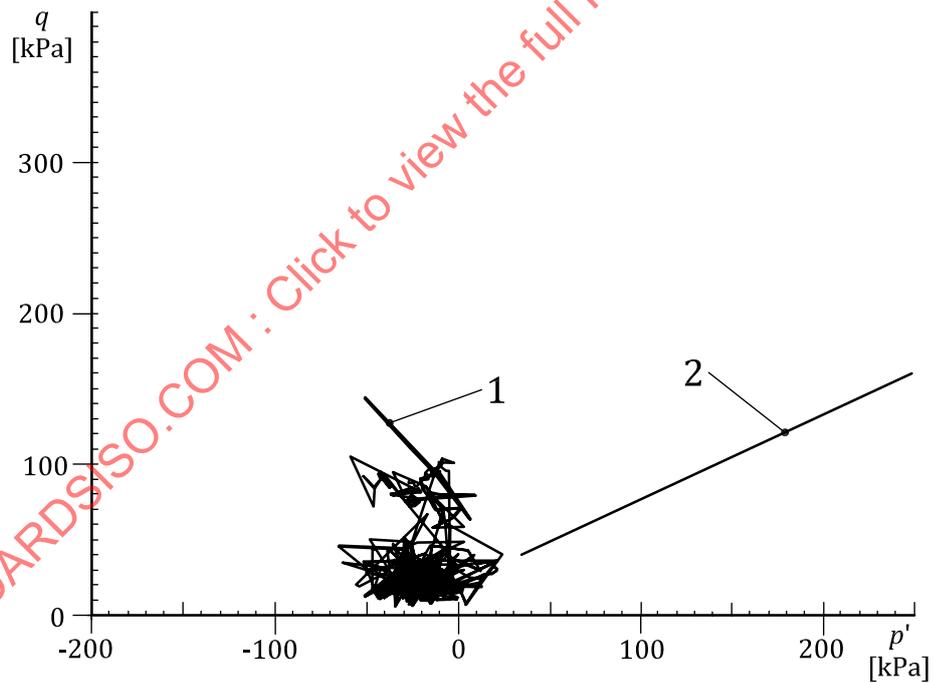
b) effective stress plot *p'-q*

Key

1   stress path

2   limiting condition (Mohr-Coulomb)

Figure C.2 — Built-up of total stresses (a) and effective stresses (b) in the clay core in course of the construction period shown in Figure C.1